AC signal sensing 6 Orders of Magnitude above Cutoff Frequency in non-equilibrium DRAM

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The development of information technology requires advanced communication and data processing technologies. In both domains, the use of high-frequency signals is one of the important factors that enable handling vast amounts of data. Devices operating in the frequency domain generally operate within specific frequency ranges, making the cutoff frequency an essential parameter to consider in the process of designing circuits. On the other hand, from the perspective of thermodynamics, non-equilibrium in an energy scale generates energy flow as like thermal gradient generates energy. This energy flow is independent of factors of time such as flow rates and time constant. As such, operating devices in the non-equilibrium domain may provide an avenue to push device performances beyond the limitations of the cutoff frequency.

In this study, we focus on the high-frequency, non-equilibrium performance of a nanoscale dynamic random-access memory (DRAM) device, in which the DRAM reads out an AC signal over six orders of magnitude above its cutoff frequency Γ_0. Fig. 1(a) shows the device, composed of a DRAM and field-effect transistor (FET) labelled the sense-FET. In the DRAM, single electrons shuttle between a nanometer-scale dot (the node) and an electron reservoir (ER). The sense-FET is capacitively coupled to the node and detects its charge. Electrons shuttling between the node and the ER induce a step-like change in the sense-FET current, as shown in Fig. 1(b). In this manner, the evolution of the number of electrons N in the node can be monitored with single-electron resolution at room temperature [1]. The addition of an AC signal on the ER changes the probability distribution of N, seen on Fig.1(c). The features of this distribution depend on the frequency f_{AC} of the AC signal as shown in Fig. 1(d): at low frequency, the average value of N, N_{av} , remains zero, although the observed variance of N, N_{var}, is large. The electrons

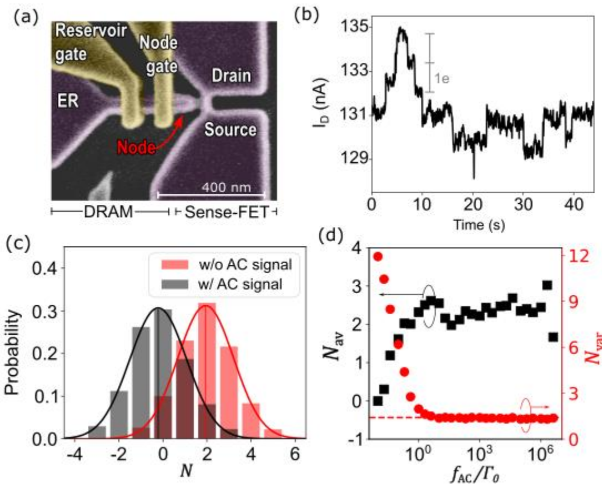

Fig.1. (a) False color scanning electron microscopy image of the device. (b) Sense-FET's current over time. Discrete jumps are visible that correspond to the number $N-\langle N\rangle$ of electrons in the node. (c) The change in the probability distribution of N with the addition of the AC signal on the reservoir when $f_{AC} \gg \Gamma_0$. Average N_{av} and variance N_{var} of $N-\langle N\rangle$, as a function of f_{AC}/Γ_0, frequency of the AC signal normalized by the DRAM's cutoff frequency.

shuttling in and out of the node follow the AC signal, the node and the BL remain in equilibrium. As f_{AC} increases beyond Γ_0, the electron shuttling no longer follows the AC signal. As a result, N_{var} saturates around $N_{var}^{(eq)}$, the value of N_{var} without AC signal, while N_{av} increases significantly compared to $N_{av}^{(eq)}$ [2]. This increase of N_{av} corresponds to an increase of the charge stored in the node, and as such the node and the BL are no longer in equilibrium. In this manner, the operation of the DRAM in the non-equilibrium regime allows the device to behave as an AC signal sensor, detecting AC signals up to six orders of magnitude beyond its internal cutoff frequency.

REFERENCES:

[1] K. Nishiguchi, et al, Jpn. J. Appl. Phys. 47, 8305 (2008).

[2] K. Nishiguchi, et al, Nanotechnology 25, 275201 (2014).